

Magnetized Flows and Self-Organization in Laboratory Plasma Experiments

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(cross-listed in P-24 Plasma Physics Summer School)

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Outline:

- Introduction to plasma physics and MHD
- Physics of plasma self-organization
- Evidence for self-organized plasmas in lab and in nature
- P-24 plasma experiments

Purpose of This Talk

- Introduce broader LANL community and summer students to plasma physics
- Seek collaborations with hydrodynamic and MHD turbulence experts

Introduction to Plasma Physics

“Plasma”

- Greek word for “formed or molded,” coined in mid-19th century by Czech physiologist Purkinje to denote clear base fluid of blood
- American scientist Langmuir adopted this term in 1922 to describe electrons, ions, neutrals in an ionized gas
- Most people think we study the physics of blood

Historical Tour of Plasma Research

1920's, 1930's: effect of ionosphere on shortwave radio;
gaseous electron tubes for rectification & switching

1940's: Alfvén waves, astrophysical plasmas

1950's: magnetic fusion energy research initiated

1960's: space propulsion research using plasma thrusters

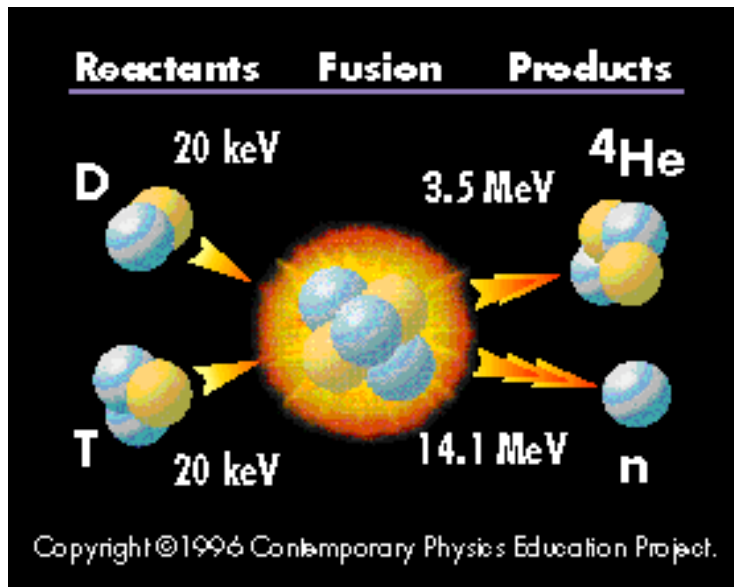
1970's: space plasma research, satellite measurements

1980's: plasma processing for semi-conductor devices

1990's: near energy break-even on research fusion reactors;
return to fundamental plasma physics as scientific discipline

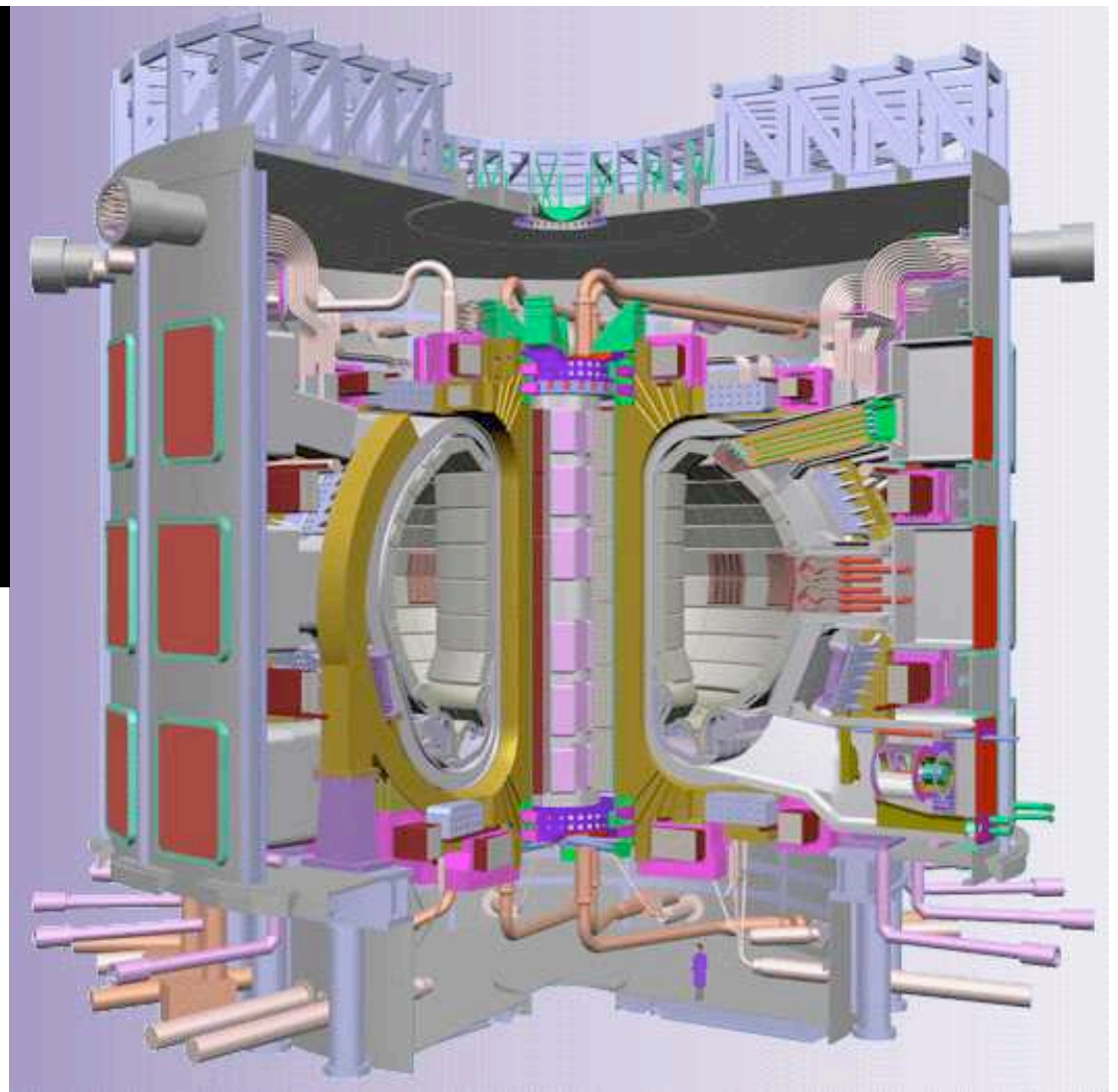
21st century: successful fusion reactor, importance of plasma
physics in astrophysics and cosmology, plasma rocket
engines for travel beyond our solar system

A Primary Driver of Plasma Physics: Controlled Thermonuclear Fusion

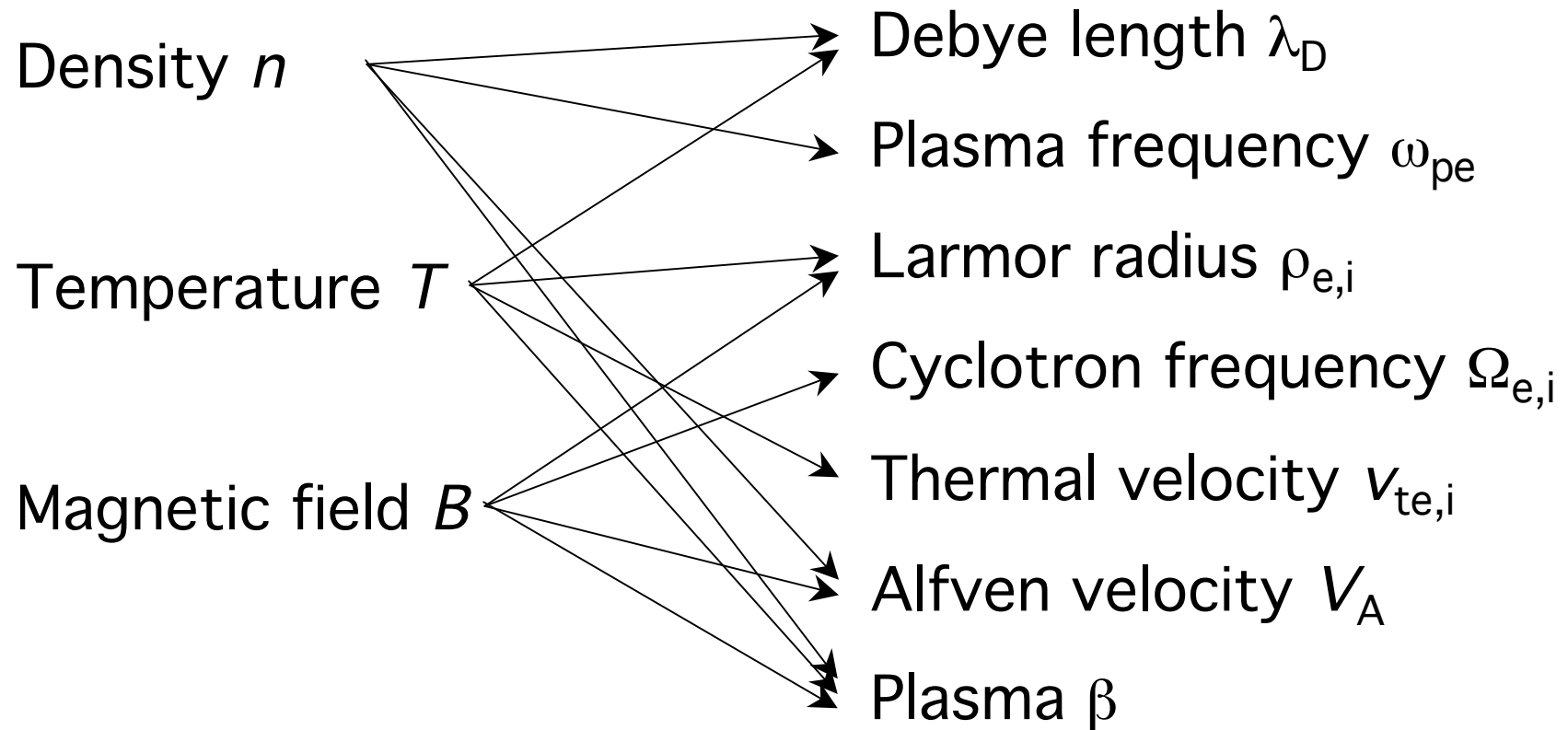


ITER

International Thermonuclear
Experimental Reactor

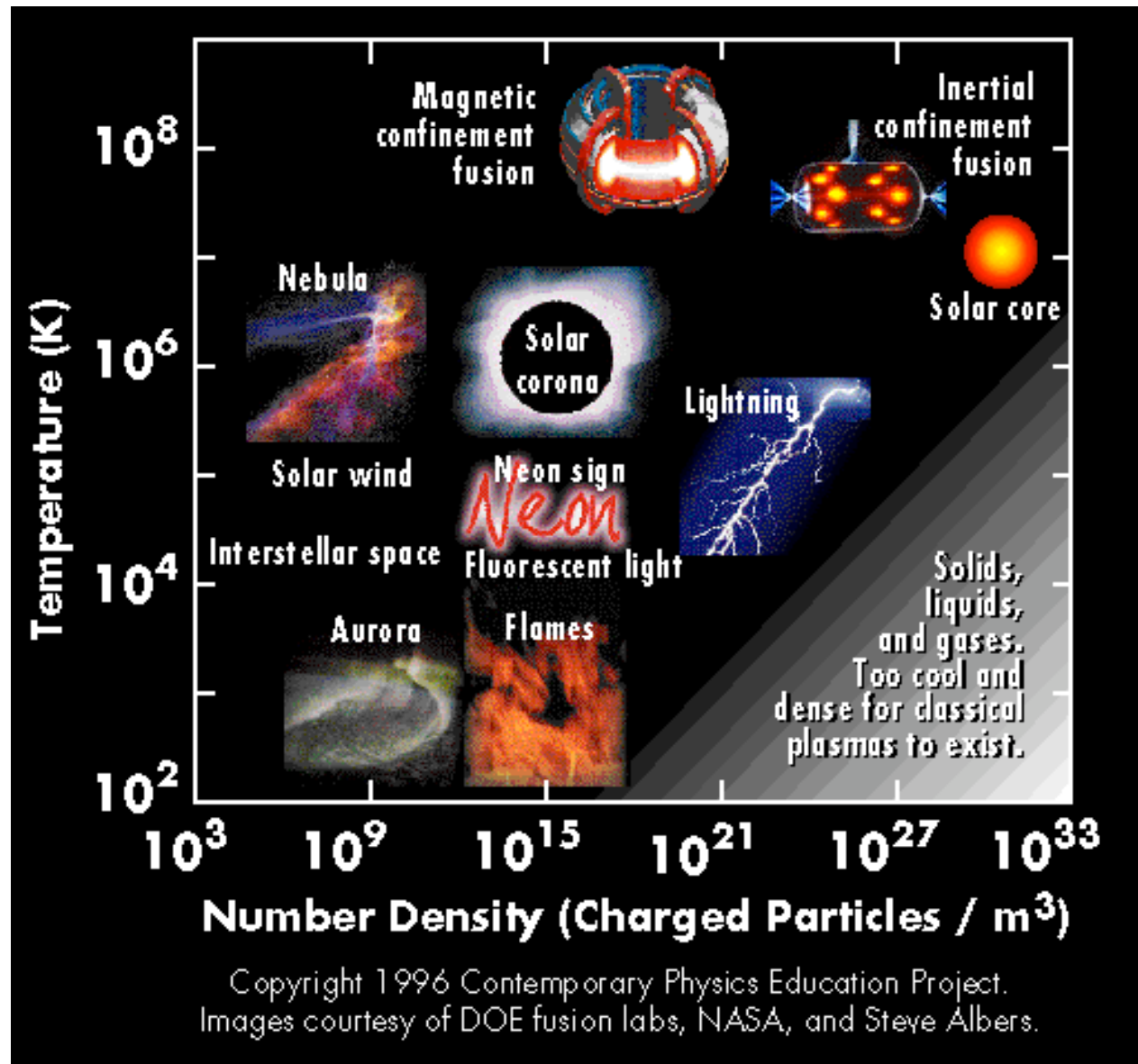


Fundamental Parameters Characterizing a Plasma



Rigorous definition of a classical plasma:
 $n\lambda_D^3 \gg 1$ and $L \gg \lambda_D$

Some Plasmas on Earth and in the Universe



Some Distinguishing Features of Plasmas

Quasi-neutrality (Debye shielding)

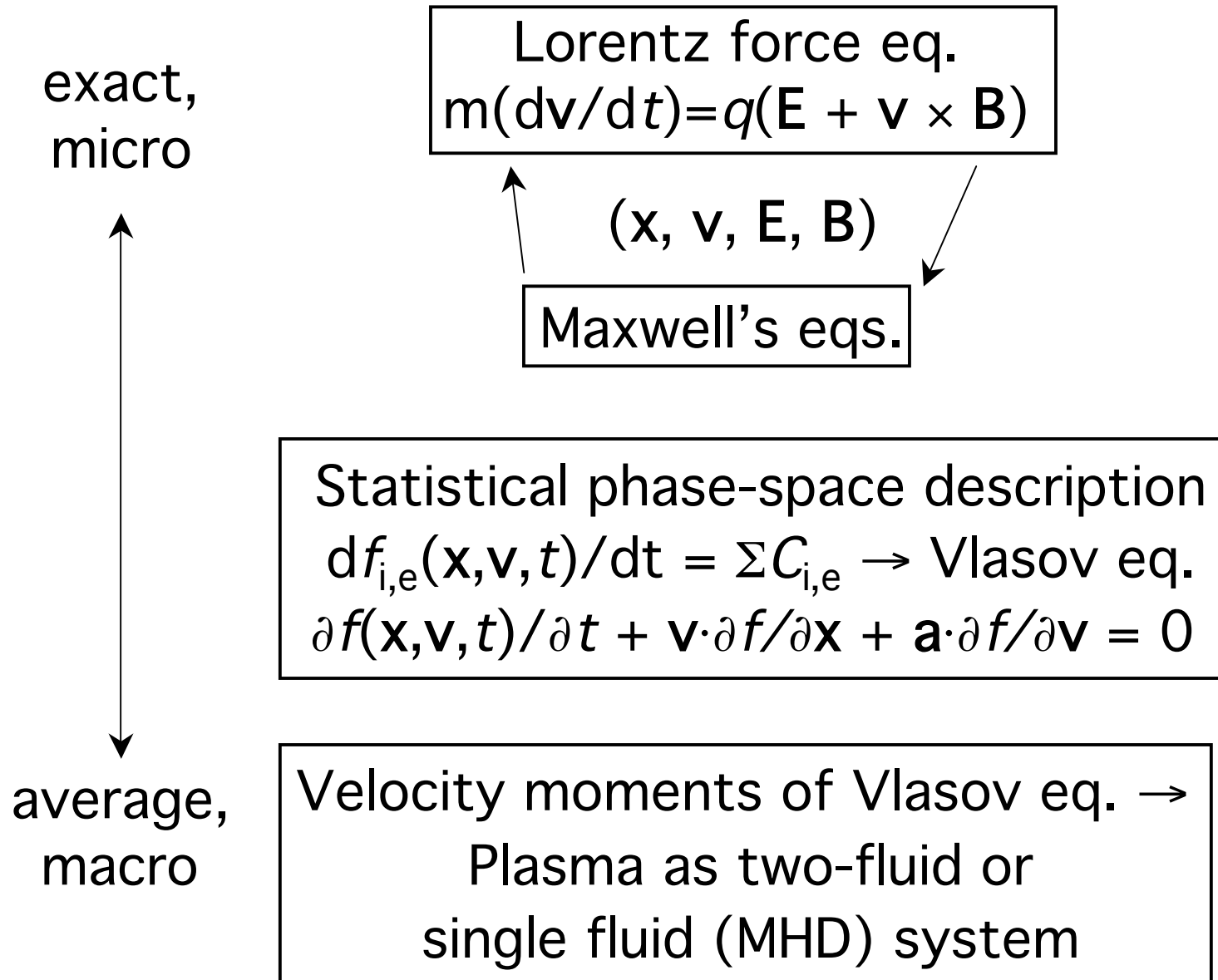
Widely varying natural length and time scales

Long range small-angle scattering dominates

Collision frequency $\sim T^{-3/2}$

Zoo of waves and instabilities

Hierarchy of Theoretical Plasma Models



Magnetohydrodynamic (MHD) Description of Plasmas

Magnetohydrodynamics

Continuity equation: $\partial\rho/\partial t + \nabla\cdot(\rho\mathbf{U}) = 0$

Force equation: $\rho[\partial\mathbf{U}/\partial t + (\mathbf{U}\cdot\nabla)\mathbf{U}] = \mathbf{j} \times \mathbf{B} - \nabla p + \rho\nu\nabla^2\mathbf{U}$

Ohm's Law: $\mathbf{E} + \mathbf{U} \times \mathbf{B} = \eta \mathbf{j}$

Maxwell's equations:

$\nabla \times \mathbf{E} = -\partial\mathbf{B}/\partial t$ (Faraday)

$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \epsilon_0 \mu_0 \partial\mathbf{E}/\partial t$ (Ampere)
 $\nearrow 0 \text{ if } V \ll c$

Eq. of state: $p/\rho^\gamma = \text{constant}$

$\partial\mathbf{B}/\partial t = \nabla \times (\mathbf{U} \times \mathbf{B}) + (\eta/\mu_0)\nabla^2\mathbf{B}$

Magnetic Reynold's number $R_m = UL/\eta$

MHD Equilibria & Stability

Static equilibria: $\mathbf{j} \times \mathbf{B} = \nabla p$

Axisymmetric ($\partial/\partial\phi=0$) \rightarrow Grad-Shafranov eq.

Zero β approx. $\rightarrow \mathbf{j} \times \mathbf{B} = 0$

$\rightarrow \nabla \times \mathbf{B} = \lambda \mathbf{B}$ (force-free)

(related to Taylor relaxed state)

Dynamic equilibria:

$$\rho(\mathbf{U} \cdot \nabla) \mathbf{U} = \mathbf{j} \times \mathbf{B} - \nabla p + \rho \nu \nabla^2 \mathbf{U}$$

Stability: Energy Principle $\delta W > 0$

Dynamics Require Nonlinear MHD

Examples:

- Resistive tearing modes (current sheet into filaments)
- Kink instability
- Magnetic reconnection
- Dynamo

Physics of Plasma Self-Organization

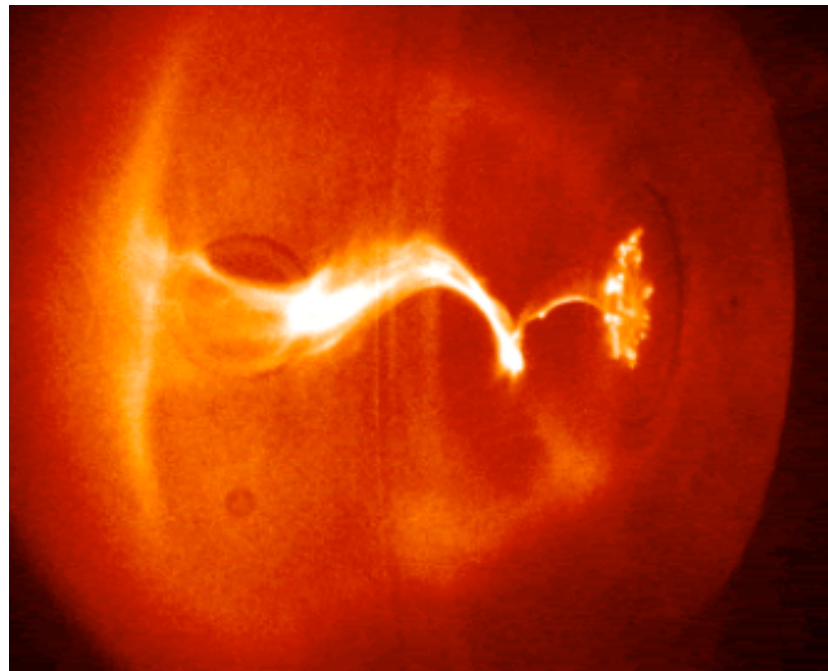
Plasma Self-Organization

Spontaneous generation of large-scale structure from homogeneous plasma turbulence

Selective decay rates of ideal invariants

Inverse spectral cascade of an ideal invariant

Plasma instabilities and microphysics



Why Study Plasma Self-Organization?

- Inspire an economic fusion reactor
- Large-scale structures in astrophysics
- Fundamental issue in turbulence

Selective Decay Rates of Ideal Invariants

$$\text{Energy } E = \int (v^2 + B^2) d^3V$$

$$\text{Cross-helicity } H_C = \int \mathbf{v} \cdot \mathbf{B} d^3V \text{ (alignment)}$$

$$\text{Magnetic helicity } H_K = \int \mathbf{A} \cdot \mathbf{B} d^3V \text{ (field twist, linkage)}$$

$$dE/dt \sim [B^2][L]$$

$$dK/dt \sim [B^2][L^2]$$

$$dE/dt = (dH_K/dt L^{-1}) \gg dH_K/dt$$

if turbulence dissipates on small scales

“Taylor Relaxation”

Tendency of plasma to evolve to preferred states
based on global constraints

Because E decays faster than H_K

formulate as variational problem

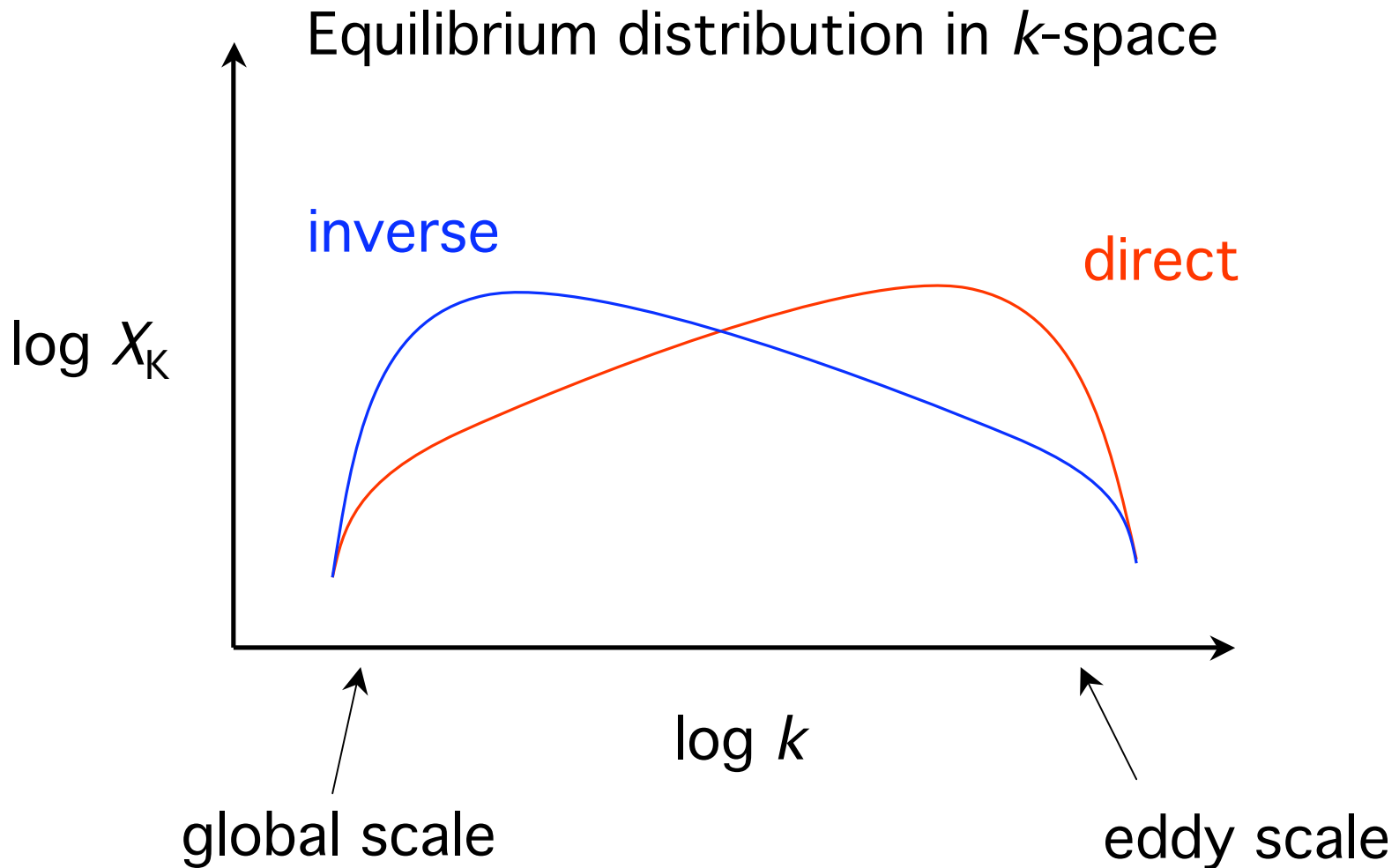
$$\delta \left(\int (v^2 + B^2) d^3V - \lambda \int \mathbf{A} \cdot \mathbf{B} d^3V \right) = 0$$

$$\rightarrow \nabla \times \mathbf{B} = \lambda \mathbf{B} \text{ (force-free state), } v = 0$$

Lowest allowed, uniform λ gives “Taylor state”

(zero β , $v = 0$)

Spectral Cascade Directions of Ideal Invariants



Self-Organization with Finite β and Plasma Flows

$$\mathbf{j} \times \mathbf{B} \neq 0$$

no longer expect force-free states

For example, flows bring in H_C

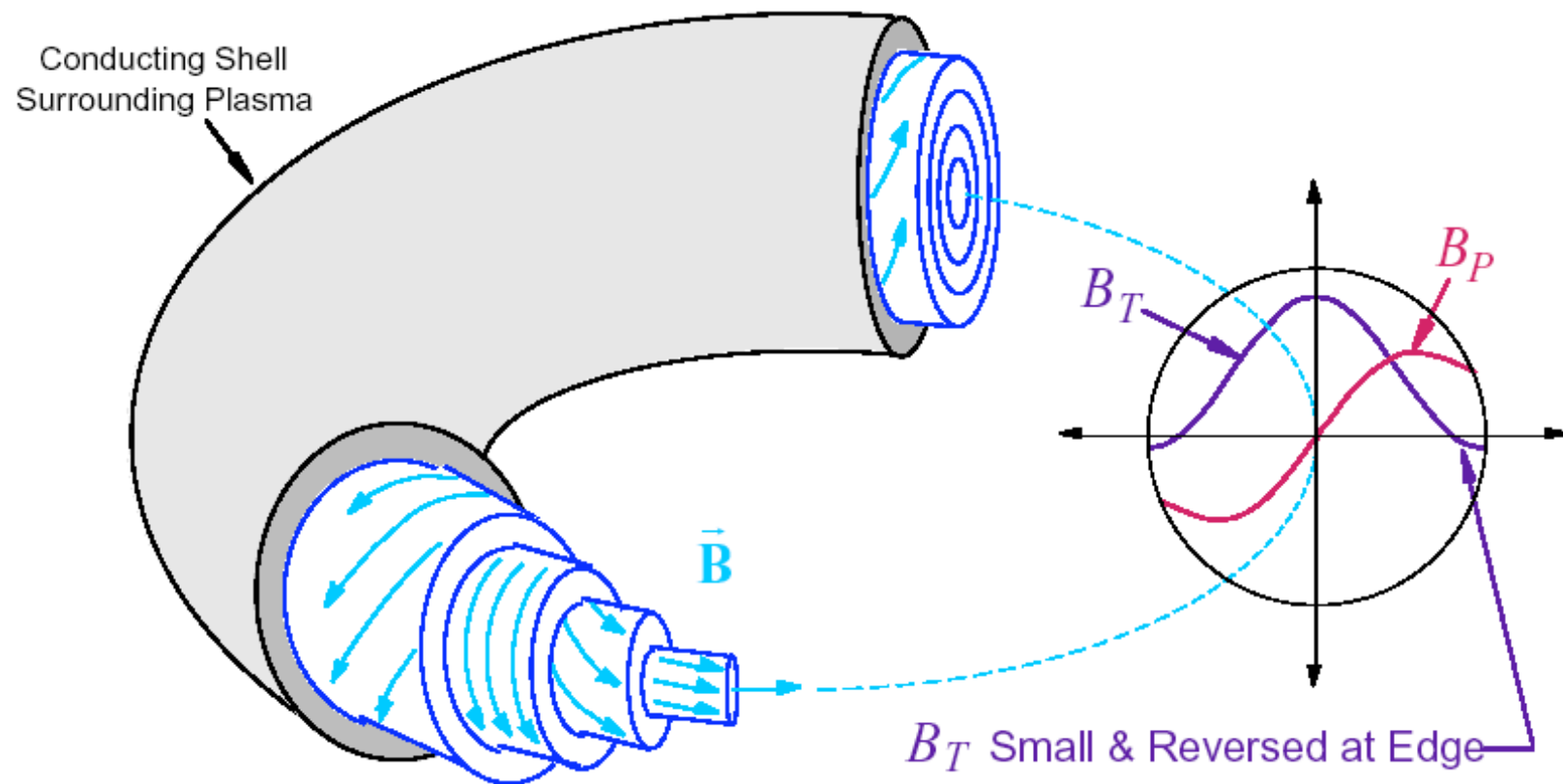
Faster decay of H_C compared to E :

$$\delta(\int (v^2 + B^2) d^3V - \lambda \int \mathbf{v} \cdot \mathbf{B} d^3V) = 0$$

$\rightarrow \mathbf{v} = \pm \mathbf{B}$ Alfvén (aligned) states

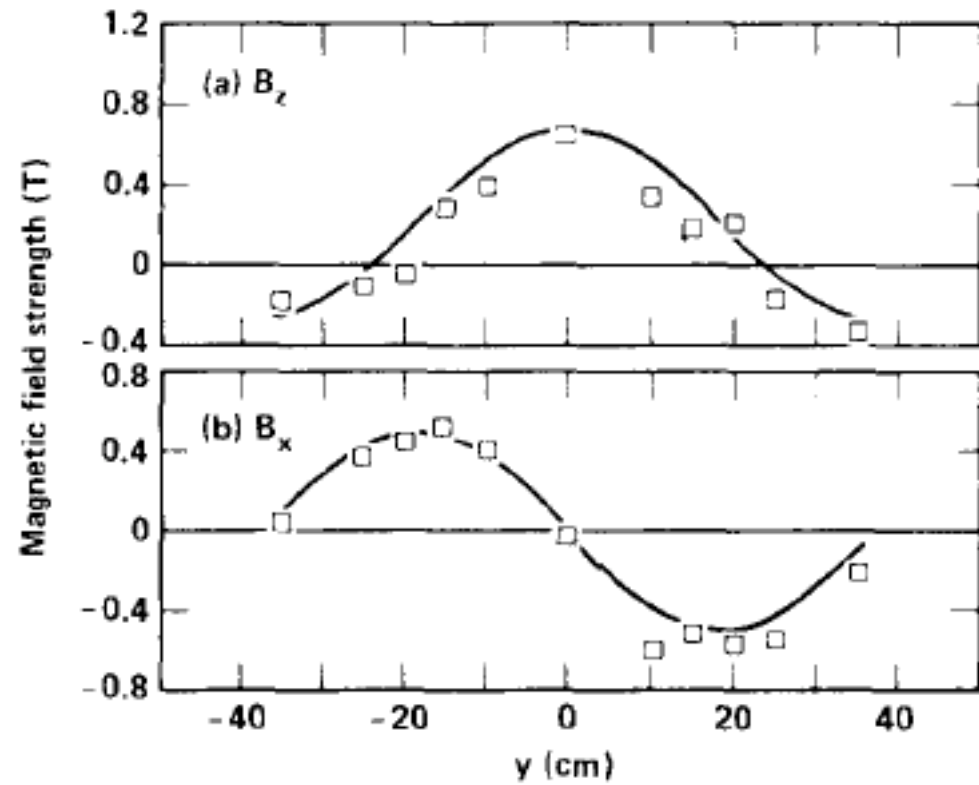
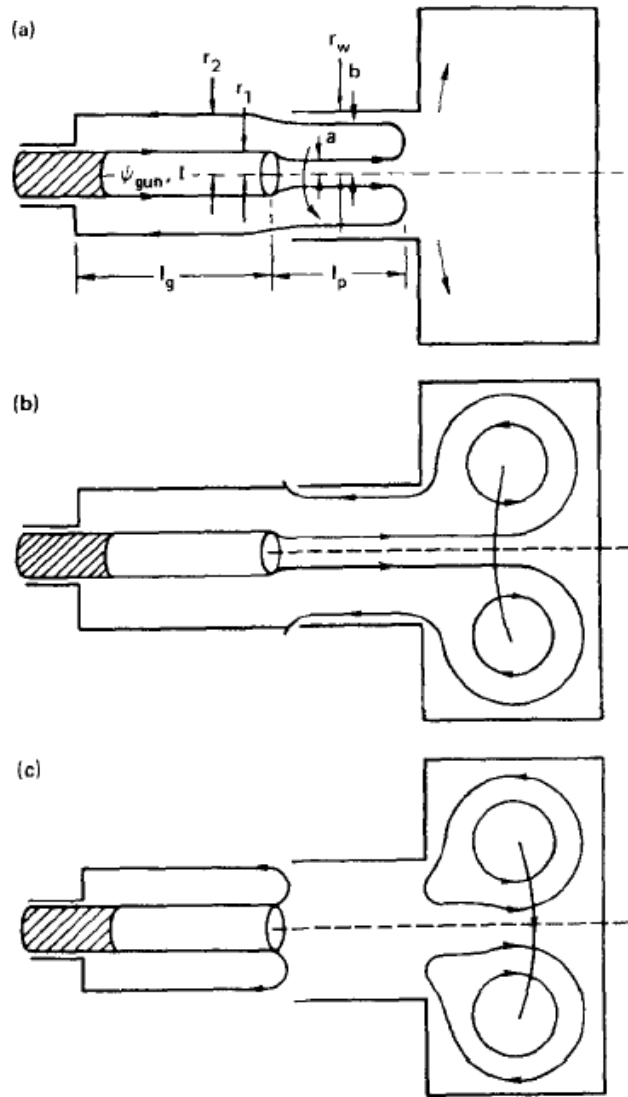
Evidence for Self-Organized Plasmas in the Laboratory and in Nature

The Reversed Field Pinch (RFP) as a Taylor Relaxed State



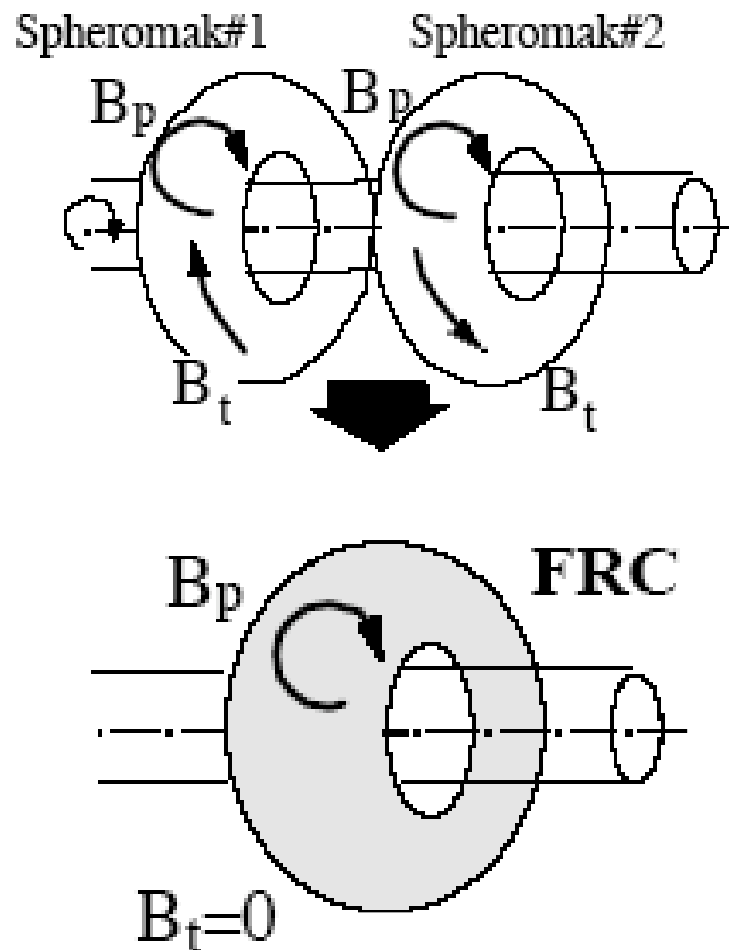
Bessel function
solutions to $\nabla \times \mathbf{B} = \lambda \mathbf{B}$

The Spheromak as a Taylor Relaxed State



Turner et al. 1983

The Field Reversed Configuration (FRC) as a Non-Taylor Relaxed State

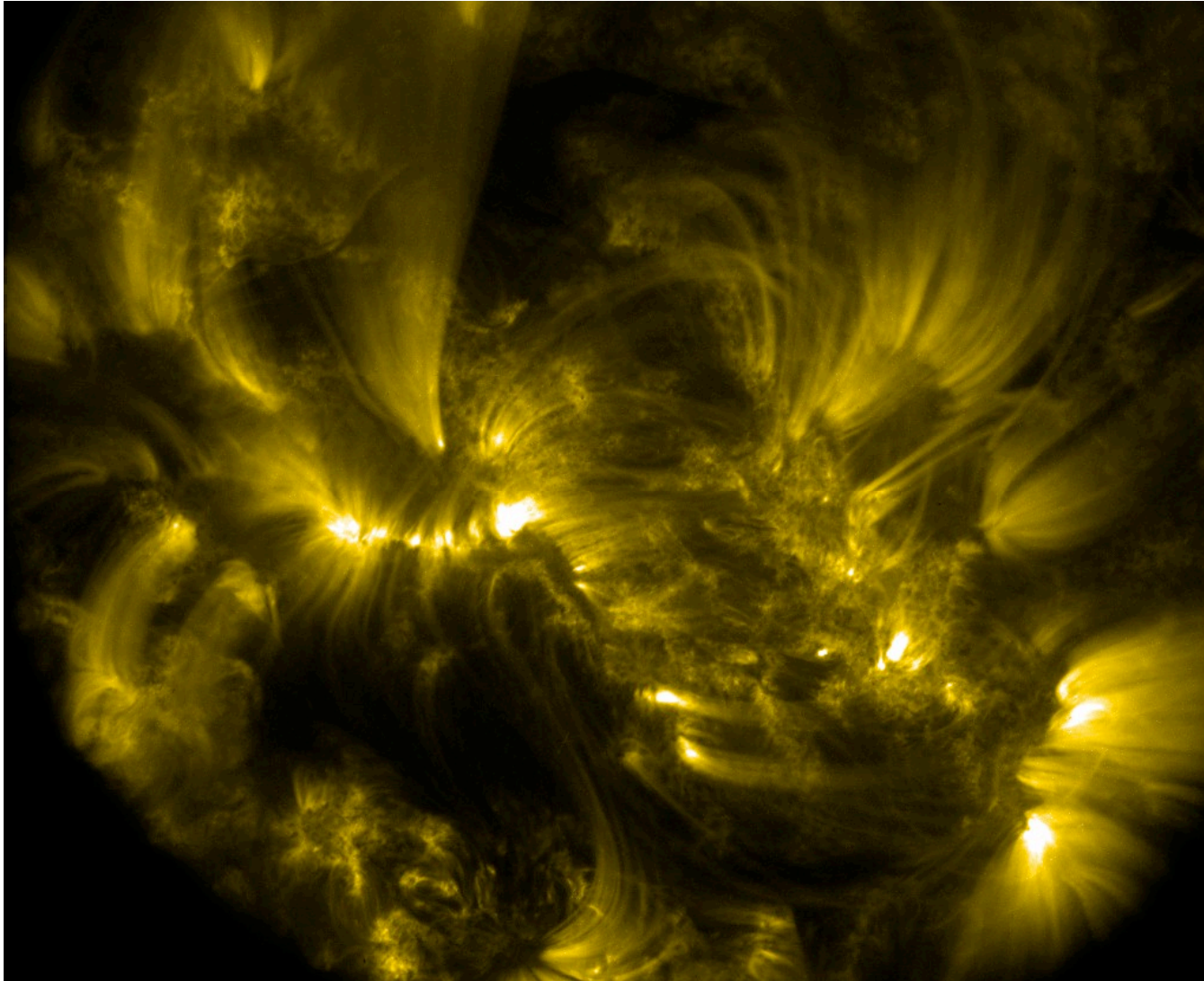


Two low- β Taylor-relaxed plasmas merge to form a high- β plasma!

Theories:

- Minimum dissipation
 $\nabla \times \nabla \times \nabla \times \mathbf{B} = \lambda \mathbf{B}$
- Two-fluid invariants: ion & electron self-helicities
($\mathbf{P}_\alpha \cdot \boldsymbol{\Omega}_\alpha$)

Solar Coronal Plasmas



TRACE satellite image 171 Å → 1 million degree plasma

Galactic (Quasar) Jets

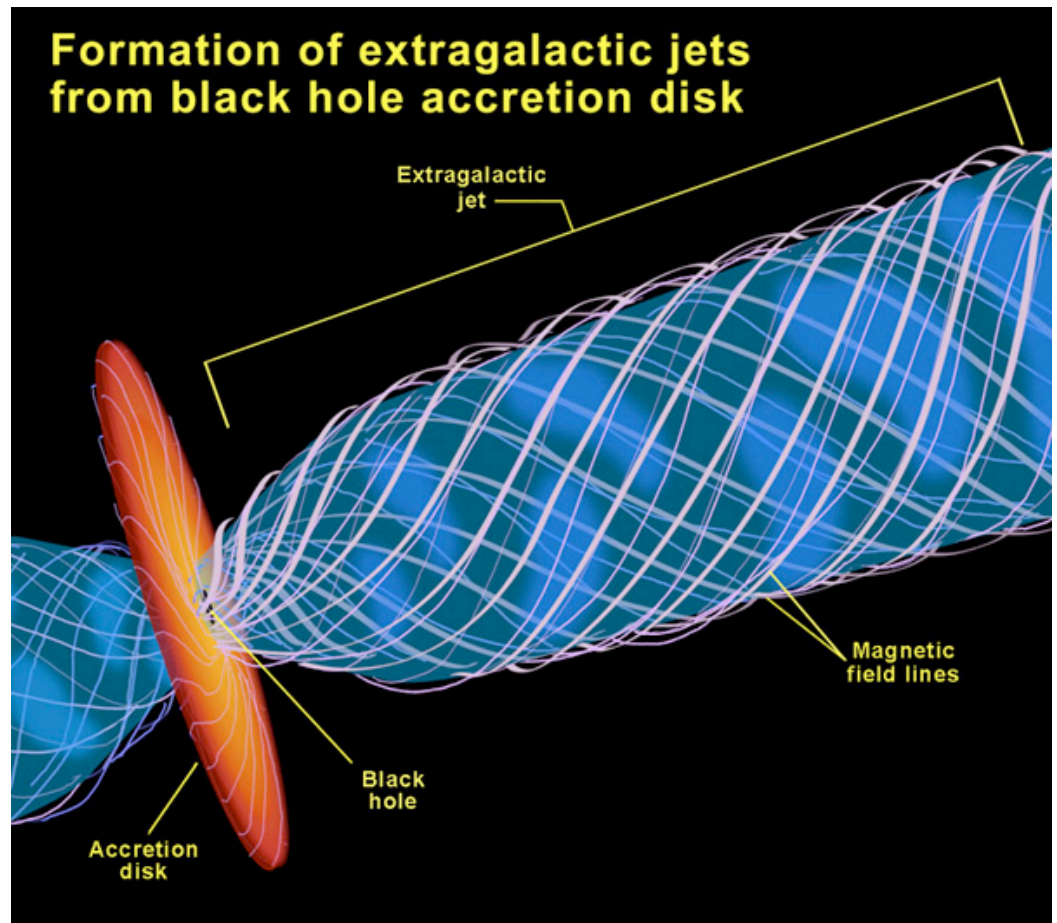


M87 jet in visible light

Credit: NASA and Biretta (1998)

Differential rotation
winds up magnetic field
in force-free plasma

Experiment has been
approved on UCLA user
facility (Hsu & Tang)



Credit: NASA

P-24 Plasma Experiments

three experiments spanning:

Plasma $\beta \ll 1$ to $\beta \sim 1$

$R_m \sim 10$ to 10^4

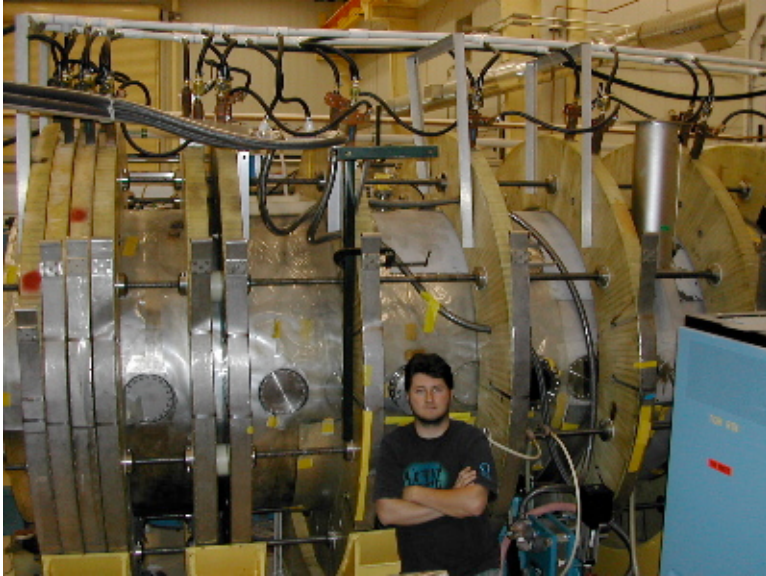
Geometries and boundary conditions

Equilibrium flow configurations

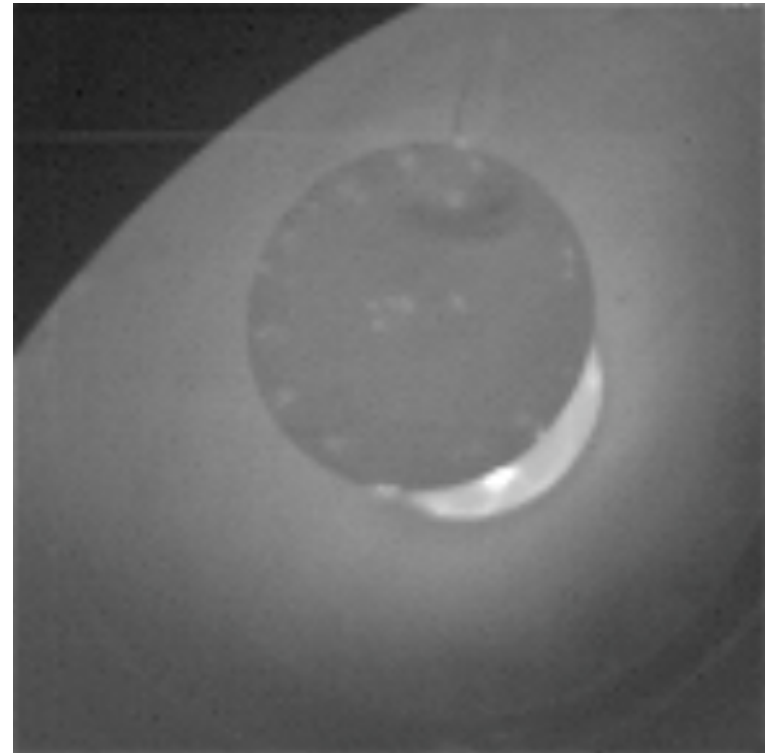
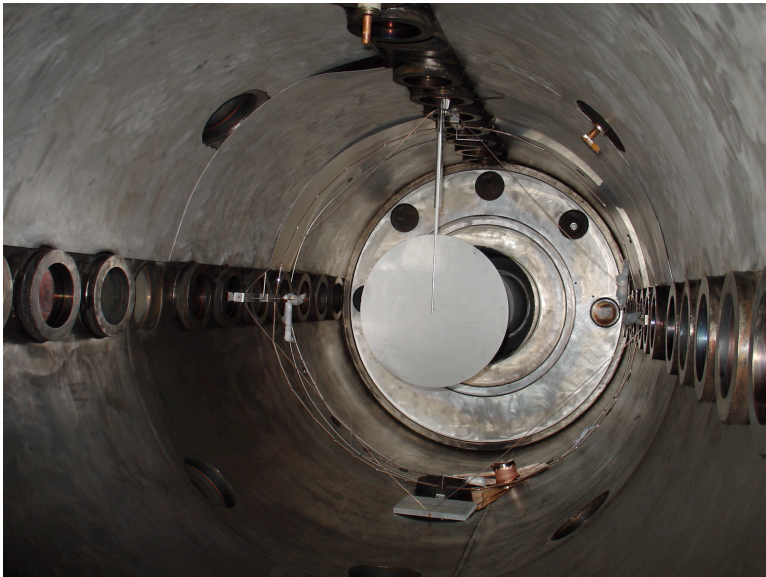
What is Needed from Experiments?

- Comparison of experiments to theoretically predicted relaxed states
- Measurements of ideal invariant decay rates
 - Single-fluid MHD (H_M , H_C)
- Equilibrium distributions of ideal invariants (cascade directions)
- What self-organization processes lead to relaxed states at high β ? With finite flows?
 - Two-fluid relaxation (self-helicities $\mathbf{P} \cdot \mathbf{\Omega}$)
 - Minimum dissipation theory
 - Conservation of cross-helicity

Flowing Magnetized Plasma Experiment

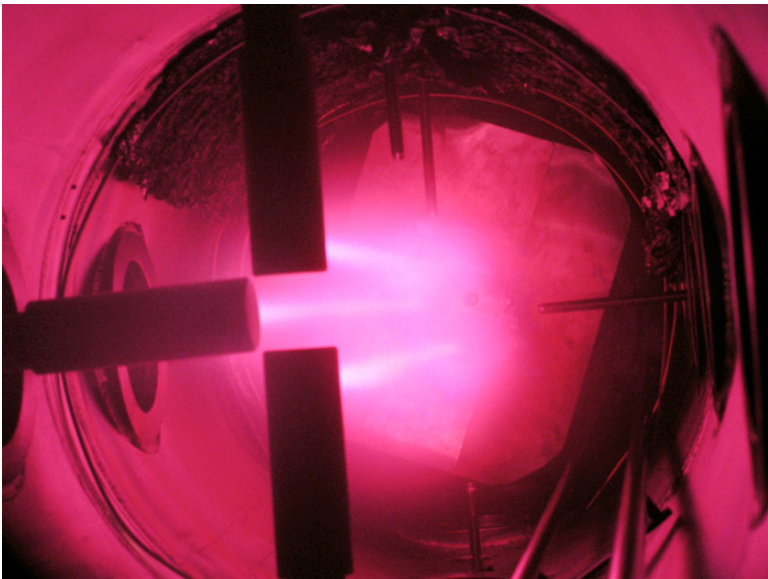
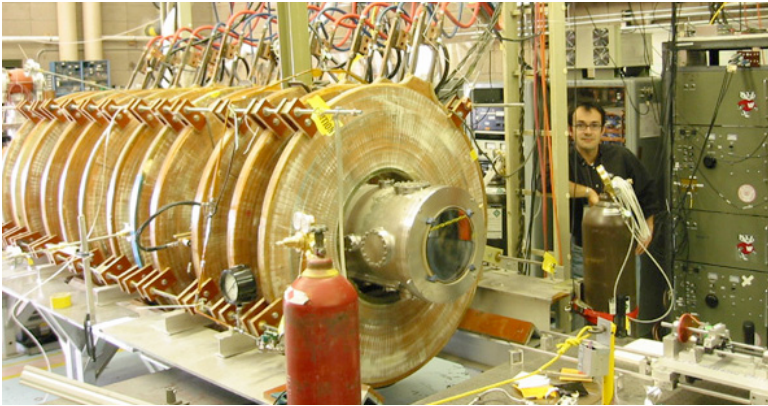


High β with strong plasma flow to study problems in plasma astrophysics

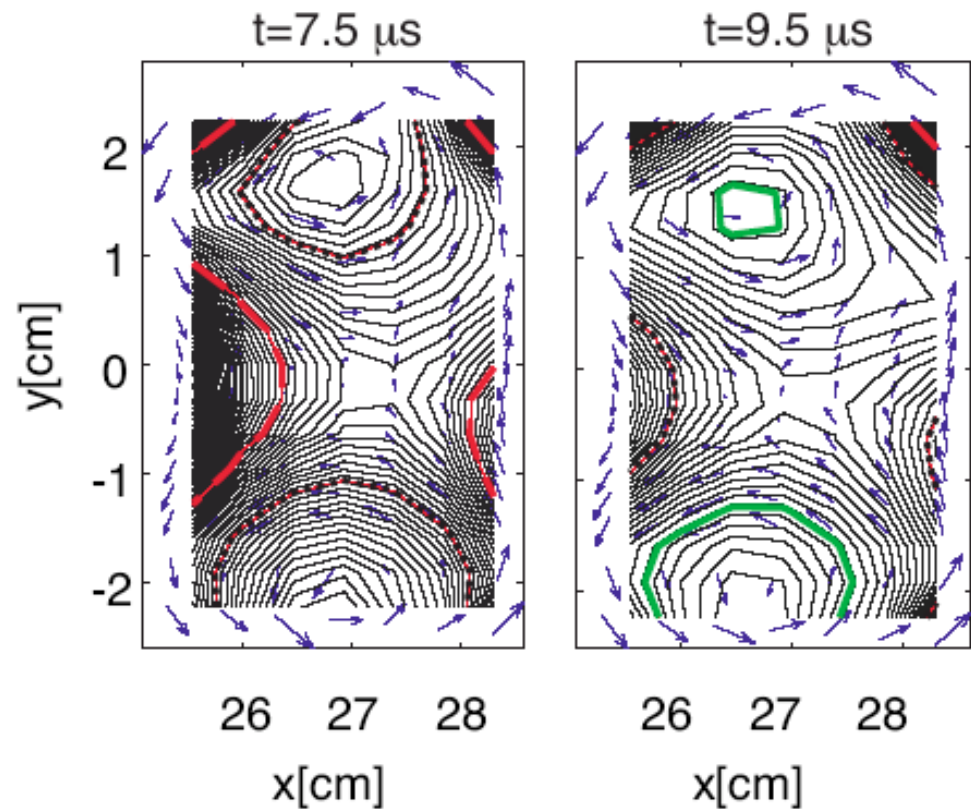


Z. Wang et al. LDRD-ER

Relaxation Scaling Experiment



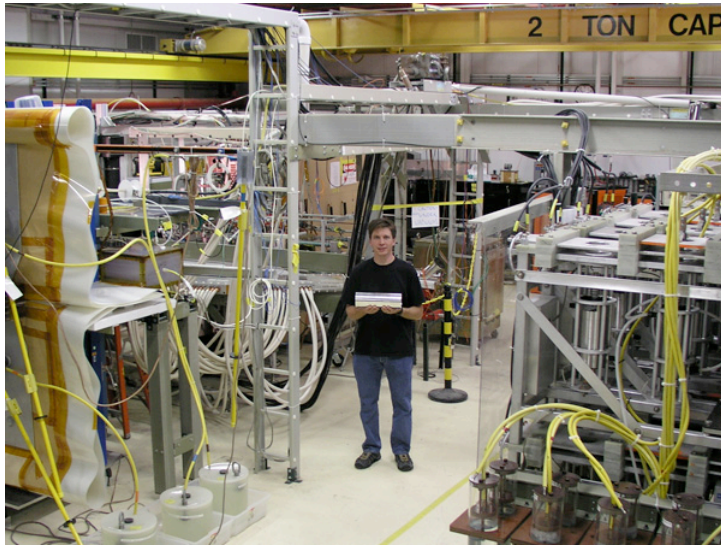
Relaxation of current-carrying plasma columns from $\beta \ll 1$ to $\beta \sim 1$



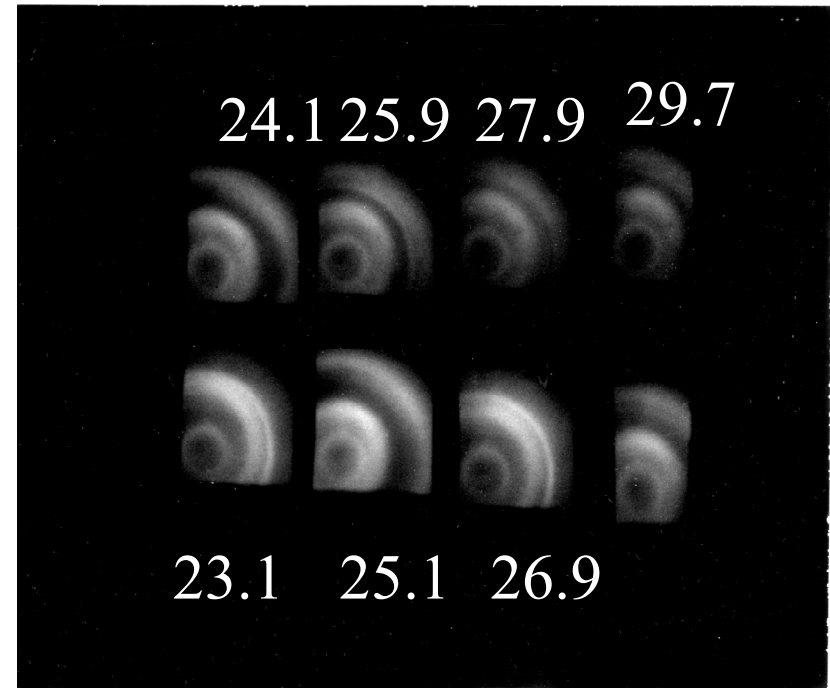
B-field measurements

Intrator, Furno et al., former LDRD-ER

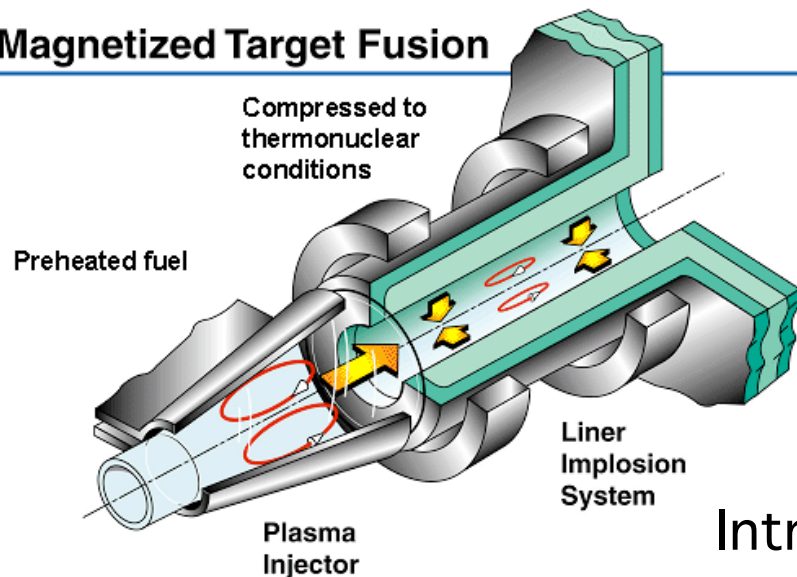
FRX-L: A High Density FRC for Magnetized Target Fusion



Form high density FRC and then
adiabatically compress to
fusion conditions



Magnetized Target Fusion



Intrator, Wurden, Zhang et al., DOE-OFES

What Can We Measure?

- Magnetic fields down to dissipation scale lengths (reconnection layers)
- Electron temperature and density (probes, Thomson scattering, interferometry)
- Ion flows and rotation (probes, spectroscopy)
- Ion temperature (spectroscopy)
- B , n , T fluctuations in time (easy) and space (harder) (probes)

Working Group Meeting to Develop Plasma Physics Research Initiative

- July 28, 10:30am-12:30pm, TA-35, Bdg 86, Rm 205
- Plasma self-organization will be key topic
- Looking for connections to fluid turbulence
- Looking for connections to code validation efforts

You Are Invited!

Summary

- Plasma physics → controlled fusion, astrophysics
- MHD, traditionally used for equilibrium and stability
- Self-organization is important aspect of nonlinear MHD and turbulence
- Plasma experiments now exist to test assumptions and predictions of turbulent self-organization theories
- We invite discussion and collaboration from hydrodynamic and MHD turbulence experts

Please contact scotthsu@lanl.gov
for references and discussions